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RESEARCH ARTICLE

Modeling the Impact of Pollution on Sea Turtles

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Abstract Human activities are currently threatening sea turtles at all life stages, both on nesting beaches and at sea. The debris and toxic waste dumped on the coast or at sea pollutes the sea and puts marine life in danger. In recent years, the number of global turtle population have noticeably decreased, and this is largely due to plastic pollution. However, how the sea pollution affects the sea turtles' populations is not fully understood. Therefore, in this study, using the mathematical model, we will investigate the impact of pollution on sea turtle population. The model system is analyzed using standard mathematical techniques, including positivity of solutions and stability analysis. Our findings showed that there are two possible equilibrium points (i.e. steady-state solutions) for the model proposed, in which the stability analysis showed that only one of the solutions is asymptotically stable. Thus, the conditions of stability for both equilibrium points were also derived analytically based on their eigenvalues. As for the numerical simulations, the parameter of contamination rate is varied to investigate the effect of pollution on the population of sea turtles. The results suggested that if the contamination rate is high, then the population of sea turtles are expected to decrease and extinct approximately within 10 years. The comparison of survival and extinction of sea turtles are shown using the time series plots.

Keywords: Mathematical model, pollution, sea turtles, stability analysis.

Introduction

In recent year, number of global turtle population have noticeably decreased, and this is largely due to plastic pollution [1]. Human activities are currently threatening sea turtles at all life stages, both on nesting beaches and at sea [2]. Litter from ships, fishing and recreational boats, and garbage carried into the sea from land-based sources in industrialized and densely populated areas are the primary sources of marine debris [3]. The debris and toxic waste dumped on the coast or at sea pollutes the sea and puts marine life in danger. The debris includes not only fishery waste such as lines, plastic ropes, and nets, but it also anthropogenic debris like as plastic bags, six pack rings, tar, styrofoam, glass, and other materials that can entangle or be eaten by sea turtles [4].

Some sea turtles are thought to be drawn to a floating, semi-transparent plastic material that is mistaken for jellyfish. It is known that if these plastics are large enough, they can lodge in the turtles' intestines, causing death or decreasing absorption from their gut, with obvious health consequences [5]. Most researchers examine dead sea turtles stranded on the beach to conduct their studies. Many researchers have reported that the common type of debris was found in sea turtles' guts is plastic [2, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]. However, others type of debris also have the high frequency. Besides, there were some sea turtles that died from being hit by boats and ships, and even got stuck in nets. Table 1 shows the ratios of number of sea turtles being captured, examined, and contaminated with marine debris for some countries around the world.

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Table 1. The proportion of sea turtles that have been contaminated from previously published articles

References /year	Region /Country	Species	Number of turtles examined, N	Turtles with ingested debris, n	Ratio, $x = \frac{n}{N}$	Proportion
Gramentz [5]	Central Mediterranean	Loggerhead	99	20	20/99	0.20
Bjorndal *et al*. [6]	Coastal Florida, USA	Green	43	24	24/43	0.56
Bugoni *et al*. [4]	Southern Brazil	Green	56	38	38/56	0.68
Tomas *et al*. [2]	Western Mediterranean	Loggerhead	54	43	43/54	0.80
Mascarenhas *et al*. [7]	Paraiba, Brazil	Olive Ridley and Green	30	30	30/30	1.00
Tourinho *et al*. [8]	Southern Brazil	Green	34	34	34/34	1.00
Guebert-Bartholo *et al*. [9]	Brazil	Green	76	53	53/76	0.70
Lazar and Gracan [10]	Adriatic Sea, Croatia	Loggerhead	54	19	19/54	0.35
Campani *et al*. [11]	Tyrrhenian Sea, Italy	Loggerhead	31	22	22/31	0.71
Hoarau *et al*. [12]	South-West Indian Ocean	Loggerhead	74	32	32/74	0.43

Several studies were conducted over several years to investigate the impact of pollution on various ecosystems using mathematical models [15]. For examples, Shukla *et al*. [16] have proposed and analyzed a nonlinear mathematical model to investigate the survival of a biological species in a dissolved oxygen-depleted water body such as a lake, caused by organic pollutant discharge. While Waghmare and Kiwne [17] presented analytical solutions for pollutant concentrations in a river that are governed by an advection diffusion equation in steady state in one horizontal dimension. Recently, Siddiqua *et al*. [18] reviewed mathematical modelling on water pollution and its effects on aquatic species. Their paper's review focuses primarily on water pollution and the effects of pollutants on aquatic species. The aim of their study is to summarize the negative effects of water pollution and the threat to aquatic species to provide a solution through mathematical modelling.

The model for studying the effects of a pollutant on local animal and plant biomass was proposed by Maystruk and Abdella [19]. The model tracks and relates changes in an animal population and its internal pollution levels, a plant population and its internal pollution levels, and the overall environmental pollution level using a system of ordinary differential equations. Furthermore, Sharma and Samanta [20] studied the dynamical behaviour of a single-species population model in a polluted environment to determine the influence of toxicants on ecological systems. They created a single-species population model using ordinary differential equations that took into account the impact of toxicants in the population and the environment. They found that, toxins in the environment have an impact on the rate of growth and carrying capacity of species.

To explore the impact of toxicants on plant biomass over time, Naresh *et al*. [21] developed and tested a nonlinear mathematical model. They assumed that toxicant absorption by plant biomass results in the production of an intermediate toxic product that has long-term effects on plant biomass. Their model is examined using differential equation stability theory and numerical simulation, and the equilibrium level of plant biomass decreases as the toxicant release rate increases. When the time delay parameter is less than the threshold value, the positive equilibrium that is locally stable without delay remains locally stable under certain conditions, but it may become unstable under other conditions, according to their findings.

Dubey *et al*. [22] suggested and analysed the effect of pollution on biological populations using a nonlinear geographic model. In these studies, it was hypothesised that contaminants enter the environment via a precursor created by the population. It is also considered that as the population grows, the precursor grows, and as the precursor develops, the pollutant grows. Their model was investigated both with and without diffusion. In the absence of diffusion, the pace of precursor formation has a significant impact on the population. The model with diffusion then shown that the system's uniform steady state is globally asymptotically stable if the equivalent steady state is globally asymptotically stable in the absence of diffusion, leading to the conclusion that global stability exists.

A nonlinear mathematical model to study the effects of mining activities and pollution on forest resources and wildlife population was proposed by Jyotsna and Tandon [23]. They formulated the model in differential equations and analyzed using stability theory and numerical simulation. Their model's results indicate that mining activities and environmental pollution in a forest area have an impact on both the densities of forest resources and wildlife populations, either directly or indirectly. Increased mining activities contribute a significant amount of pollutants in dense forest areas while also reducing forest cover area.

From the literature, the mathematical models had proven effective in solving pollution problems. However, as far as we concern, the model to study the impact of pollution on sea turtles has not been done yet. Therefore, in this study, we will propose a simple mathematical model to study the impact of pollution on sea turtles theoretically by using the ordinary differential equation.

Model Development

In this research, we formulate a simple mathematical model to describe the effect of pollution (marine debris) on sea turtle population. Figure 1 shows the flow diagram of relationship between the sea turtles (denoted by $S(t)$) and the amount of pollutants (denoted by $P(t)$). Five parameters were involved which are r, K, a, b and U in which all of them are nonnegative. The description of these parameters is listed in Table 2.

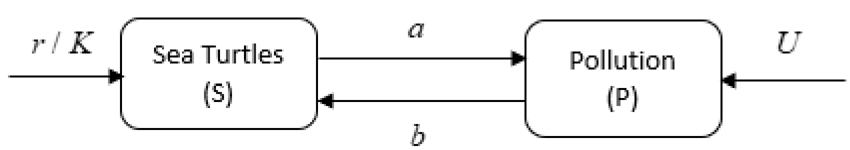

Figure 1. Relationship diagram between sea turtles and pollution

Table 2. Description of parameters for model (1)

Parameter	Description
r	Growth rate of sea turtle population
K	Carrying capacity
a	Contamination rate
U	Input rate of pollution (marine debris)
b	Absorption rate of pollution into sea turtles' body

From Figure 1, we assume that the population of sea turtles, $S(t)$, is increased by the growth rate r and limited by carrying capacity K, and may decreased due to pollution with contamination rate a. Whereas, the concentration of pollution $P(t)$ is increased by the input rate of pollution U, and it will be absorbed into the sea turtles' body with rate b. Therefore, the dynamics of sea turtles and pollution can be written as follows:

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$$\frac{dS}{dt} = rS\left(1 - \frac{S}{K}\right) - aSP,$$
$$\frac{dP}{dt} = U - bPS, \tag{1}$$

with initial data $S(0) > 0$ and $P(0) > 0$. In the following theorem, we prove the positivity of solution for model (1). This proof is crucial to ensure that the solution is biologically meaningful.

Theorem 1. *The solution $G(t) = (S(t), P(t))$ is non-negative for all $t > 0$ if the initial data of system (1), $G(0) = (S(0), P(0))$ is non-negative.*

Proof. To show the positivity of the state $S(t)$, we first rewrite the first equation of system (1) as:

$$\frac{dS}{dt} + \left[aP - r\left(1 - \frac{S}{K}\right)\right] S = 0 \tag{2}$$

Integrating of Equation (2) with respect t to get

$$S(t) = S_0 e^{-\int_0^t aP - r\left(1 - \frac{S}{K}\right) dt} \geq 0 \tag{3}$$

From Equation (3), we observe that $S(t)$ is non-negative for all $t > 0$ since $S_0 > 0$ and $e^{-\int_0^t aP - r\left(1 - \frac{S}{K}\right) dt} > 0$. Now, we show the positivity for the state $P(t)$. In a similar procedure, the second equation of system (1) can be written as

$$\frac{dP}{dt} + [bS]P = U \tag{4}$$

Integrating of Equation (4) with respect t to get

$$P(t) = \frac{U \int_0^t e^{\int_0^t bP\, dt}}{e^{\int_0^t bP\, dt}} \geq 0 \tag{5}$$

From equation (5), we observe that $P(t)$ is also non-negative for all $t > 0$ since $U > 0$ and $e^{\int_0^t bP\, dt} > 0$.

Thus, it is proven that $S(0) > 0$ and $P(0) > 0$. ■

Equilibrium and Stability Analysis

Equilibrium analysis is essential to obtain the stability of our model. Therefore, to find the equilibrium points for model (1), we take the equations equal to 0 and solve the variables simultaneously for $S(t)$ and $P(t)$. There are two possible equilibrium points for this model in the form of $E = \big(S(t), P(t)\big)$:

$$E_1 = \left(\frac{bKr + \sqrt{b^2k^2r^2 - 4UabKr}}{2br}, \frac{2Ur}{bKr + \sqrt{b^2k^2r^2 - 4UabKr}}\right), \tag{6}$$

$$E_2 = \left(-\frac{-bKr + \sqrt{b^2k^2r^2 - 4UabKr}}{2br}, -\frac{2Ur}{-bKr + \sqrt{b^2k^2r^2 - 4UabKr}}\right) \tag{7}$$

Next, stability analysis is performed to classify the stability equilibria E_1 and E_2. The stability of equilibrium points is determined based on the eigenvalues obtained from the Jacobian matrix, i.e. the partial derivatives for model (1). The Jacobian matrix for system (1) is given by:

$$J(S^*, P^*) = \begin{pmatrix} r\left(1 - \frac{S}{K}\right) - \frac{rS}{K} - aP & -aS \\ -bP & -bS \end{pmatrix}. \tag{8}$$

From this matrix, the eigenvalues, λ for each equilibrium points, E is determined using the formula:

$$\det(J - \lambda I) = 0, \tag{9}$$

where I is a 2 by 2 identity matrix. From the theories, we can classify the equilibrium points from Definition 1:

Definition 1. Let λ_1 and λ_2 are the eigenvalues obtained from Equation (9);

- If all the eigenvalues have negative values, $(\lambda_1, \lambda_2 < 0)$, then the equilibrium points, E is asymptotically stable.
- If at least one of the eigenvalues is positive, $(\lambda_1 < 0, \lambda_2 > 0)$ or $(\lambda_1 > 0, \lambda_2 < 0)$, then the equilibrium points, E is saddle and implies the unstable condition.
- If all the eigenvalues have positive values, $(\lambda_1, \lambda_2 > 0)$, then the equilibrium points, E is unstable.

To find the eigenvalues for the first set of equilibrium points, E_1, the corresponding values for S and P is substitute into Equations (8) and (9). Thus, we have a set of eigenvalues for E_1 as:

$$\lambda_{1,2} = -\frac{1}{4\,A}\left((Kb + r)\left(A + \sqrt{C}\right) \mp \sqrt{2\,A(Kb - r)^2\left(A + \sqrt{C}\right) - 4aUA((Kb - r)^2 - 4A)}\right). \tag{10}$$

where $A = Kbr$ and $C = A^2 - 4aUA$. From Equation (10), we notice that if $C > 0$, both $\lambda_1 < 0$ and $\lambda_2 < 0$, which make equilibrium points, E_1 is asymptotically stable. In contrast, if $C < 0$, results in $\lambda_1 > 0, \lambda_2 < 0$ or $\lambda_1, \lambda_2 > 0$ which implies unstable condition.

Then, using the similar approach in finding E_2, we have a set we have a set of eigenvalues for E_2 as:

$$\lambda_{1,2} = -\frac{1}{4\,A}\left((Kb + r)\left(A - \sqrt{C}\right) \mp \sqrt{2\,A(Kb - r)^2\left(A - \sqrt{C}\right) - 4aUA((Kb - r)^2 - 4A)}\right). \tag{11}$$

From Equation (11), we notice that if $C > 0$, $\lambda_1 > 0$ and $\lambda_2 < 0$, which make equilibrium points, E_2 is saddle and implies the unstable condition. The similar condition also occurs if $C < 0$, results in $\lambda_1 > 0, \lambda_2 < 0$ or $\lambda_1, \lambda_2 > 0$ which also implies unstable condition. Therefore, we have the following corollaries:

Corollary 1. *The first set of equilibrium points, E_1 is asymptotically stable if and only if $C > 0$.*

Corollary 2. *The second set of equilibrium points, E_2 implies unstable condition for both $C > 0$ or $C < 0$.*

From Corollary 1, if $C > 0$, then $A^2 - 4aUA > 0$ which implies that $a < \frac{A^2}{4UA}$.

The numerical results based on the equilibrium points and the stability analysis will be discussed in the next section.

Results and Discussion

From our theoretical analysis, we observed that there are two equilibria in the model (1). We conducted stability analysis on the equilibria and based on the results from Corollaries 1 and 2, it is shown that the contamination rate, a, plays an important role in determining the dynamics of model (1). Thus, to validate these theoretical results, in this section, we conducted the numerical simulation to further examine the dynamical behavior of the proposed model. The numerical simulation for model (1) is implemented using Maple software. The values of parameters used as our input to calculate the eigenvalues and their stability are shown in Table 3. It is noted that the value of contamination rate parameter a is computed from the average of all ratios from Table 1. In this study, we investigate this parameter for region $a \in [0,1]$. Since we believe that the number of pollutants doubles every year, we utilise the input rate of $U =$

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2. Assuming that half of the pollution is absorbed into the bodies of sea turtles, we have chosen an absorption rate of $b = 0.5$.

Table 3. Values of parameters for model (1)

Parameter	Values	References
r	0.2174	Mohd Roslan *et al*. [24]
K	100	Saifuddin *et al*. [25]
a	0.643	Computed from literature (See Table 1)
U	2	Assumed
b	0.5	Assumed

Equilibrium Points and Their Stability

Using the parameters in Table 3, the results of stability based on equilibrium points in Equation (6) and (7), eigenvalues in Equations (10) and (11) and Corollaries 1 and 2 are summarized in Table 4. From the table, we can show that E_1 is stable while E_2 is unstable. This indicates that in the future, E_1 will occurred while E_2 is not. It is also estimated that there will be 93.7≈ 94 sea turtles in the future based on the input in Table 2. In fact, for $a = 0\ldots1,\ E_1$ is always stable since both eigenvalues are negative, while E_2 is always unstable for this range.

Table 4. Eigenvalues and types of stability for equilibria in model (1)

Equilibrium point	Eigenvalues	Types of Stability
$E_1 = (93.7, 0.02)$	$\lambda_1 = -0.19, \lambda_2 = -46.9$	Stable
$E_2 = (6.31, 0.317)$	$\lambda_1 = 0.179, \lambda_2 = -3.35$	Unstable

Effect of Varying the Contamination Rate a in Model (1)

In this section, we vary the contamination rate a from 0 to 1, with the initial value of sea turtles, $S(0) = 10$ and initial pollution, $P(0) = 2$ to examine the impact of contamination rate to the sea turtle's population. The dynamics on varying parameter a are represented in time series plots. The time series are plotted for $a = 0$ (Figure 2), $a = 0.3$ (Figure 3), $a = 0.643$ (Figure 4) and $a = 1$ (Figure 5).

First, we investigate when there is no presence of pollution concentration at all (i.e., $a = 0$) in the ocean. From Figure 2, it is obvious to see that the number of sea turtle population will increase logistically from year to year, and finally the population achieved at its own carrying capacity $S^* = K = 100$. This means that the sea turtle population can be sustained in the future if we can guarantee that there is no pollutions, especially marine debris in the sea water. Then, in the presence of low contamination rate (i.e., $a = 0.3$), we can see from Figure 3 that the sea turtle population is expected to increase in time but with slower pattern. At this stage, the population of sea turtle can still be maintained in the future.

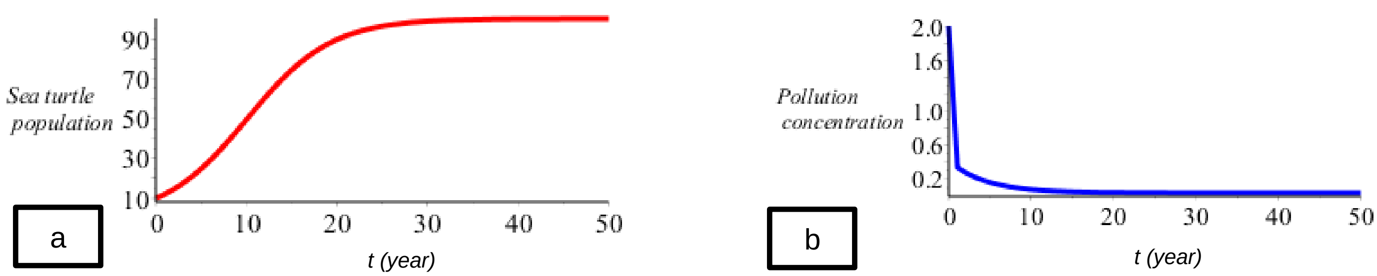

Figure 2. Time series plots for (a) sea turtle's population vs time and (b) pollution concentration vs time at $a = 0$

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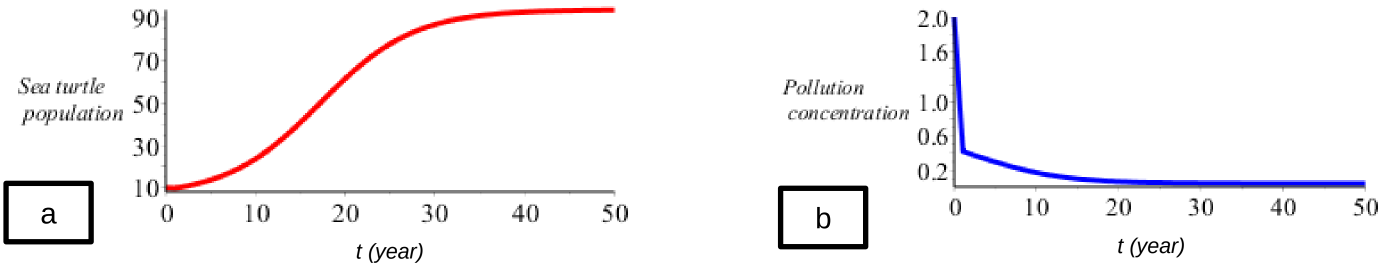

Figure 3. Time series plots for (a) sea turtle's population vs time and (b) pollution concentration vs time at $a = 0.3$

Unfortunately, when the value of the contamination rate equal to absorption rate of pollution into sea turtles' body, $a = b$, we can see that sea turtle's population decrease and expected to extinct after 10 years as shown in Figure 4(a). Further, we can also see that, the pollution concentration also increases rapidly after 10 years. Figures 5-6 also shows the similar pattern of current state of the future of sea turtles (i.e., $a = 0.643$). At this stage, the populations decrease from time to time and expected to extinct within less than 10 years. Meanwhile, the level of pollution concentration is increasing unboundedly as time goes by. Even worse, if the contamination rate increase to $a = 1.0$, this means that the sea water is highly polluted with marine debris. This makes the population of sea turtle decrease abruptly and may extinct within less than 5 years (see Figure 6).

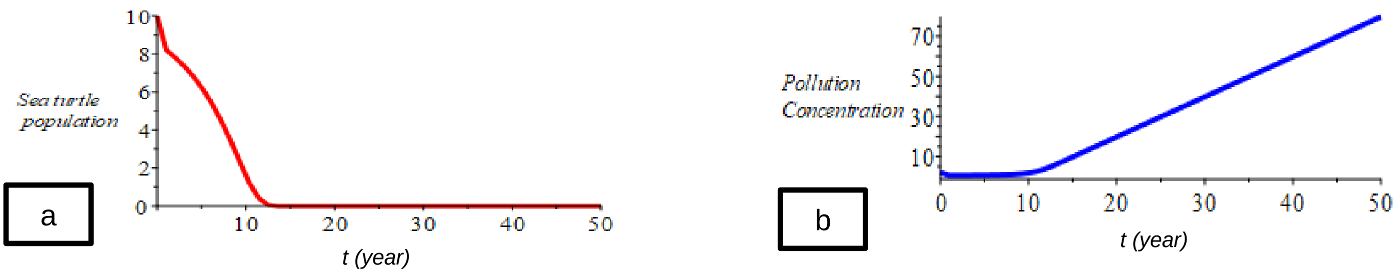

Figure 4. Time series plots for (a) sea turtle's population vs time and (b) pollution concentration vs time at $a = 0.5$

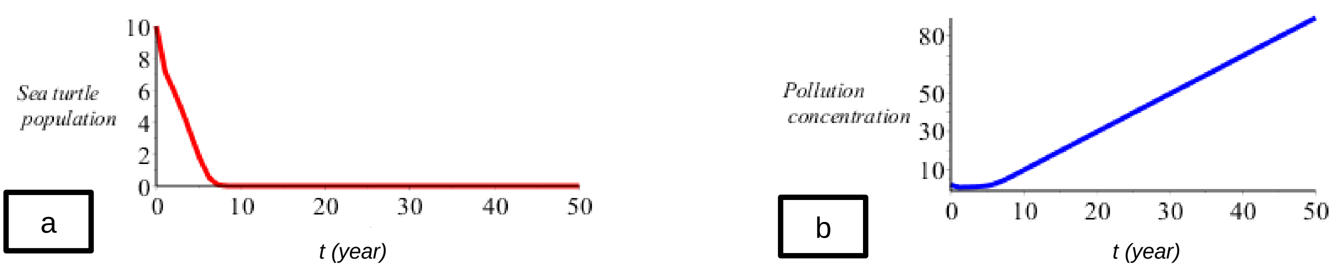

Figure 5. Time series plots for (a) sea turtle's population vs time and (b) pollution concentration vs time at $a = 0.643$

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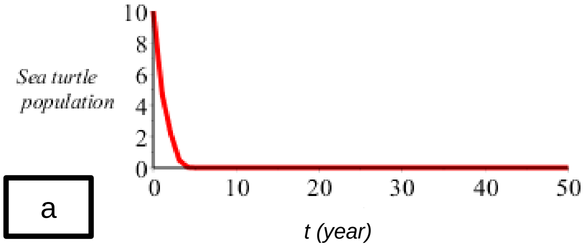
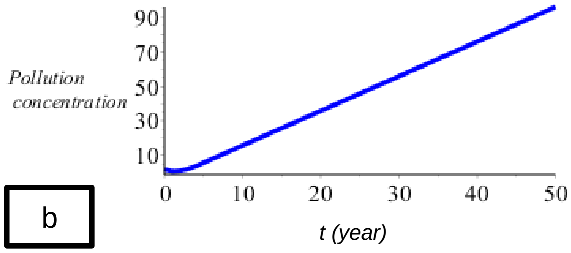


a



b

Figure 6. Time series plots for (a) sea turtle's population vs time and (b) pollution concentration vs time at $a = 1$

Conclusions

As far as we concerned, there is no mathematical model studying the impact of pollution on the population of sea turtle. Therefore, in this work, we proposed a new simple mathematical model on investigating the relationship between the sea turtle population with pollution concentration, i.e. the marine debris. We examine the influence of contamination rate produced by the marine debris, on the population of sea turtles. The data was obtained for some countries in the world. We first proved that the model proposed has non-negative solutions so that the model is biologically reasonable. It is observed that the model has two possible equilibria in which one of them is always asymptotically stable while the other is always unstable, for a region of contamination rate parameter $a \in [0,1]$. Furthermore, we also varying the contamination rate a by representing time series plots for different a. Our current situation shows that the population of sea turtle is expected to decrease and might extinct in less than 10 years. This is a critical situation in which the sea turtles will not be sustained in the future. Overall, the use of mathematical modelling approach is important in order to better understand the relationship between sea turtle population with pollutants. The knowledge extracted from this work can help to support authorities in making decision so as to control the level of pollutants in the sea water. This is crucial in helping to sustain the population of sea turtles so that our future generations can still appreciate the existence of such unique creatures.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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